Solar Storms: Risks to Electric Power Systems

Expert Hearing on Solar Storms, Electric Power Systems

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Discussion Topics Outline

• Power System Limits: Self-Preservation Conflict
  - Simultaneity vulnerability

• Solar Storms: - Coupling to Earth
  - Coupling to Power Systems
  - Solar Variations

• Models: Features, Uncertainties

• Apparatus: Heating, Harmonics

• Key Limits/Actions Today: Models, Impact Calculations
‘Bad’ Things Do Happen !!!

How to be Prepared?

Desert Wells Nevada
Via: University Libraries
University of Nevada
Nevada Magazine 2016
Core Concepts for GMD Power System Risks

1. Inherent Collapse due to Self – Preservation
   A) Wide-area recovery process, Black-starts

2. Abnormal Injected Perturbation Energy

3. Inadequate Models

4. Unknown / Variable Parameters

5. Unknown Solar Event Size/Extent
Power System:
Two Major Conflicting Requirements:

1. Protect itself from Self-Destruction

2. Always supply electric power to customers

In the end ‘1’ takes Priority:
(Temporary Collapse vs ‘Permanent’ Damage)

(Example: The sudden SIMULTANEOUS outage of ‘3 or more’
large sources will bring most power systems to collapse.)
The biggest risk from Large GMD Events is Tipping Point; ‘Simultaneity’

1. The system designed to tolerate ‘local’ failure

2. The system cannot tolerate many ‘source’ failures over a wide area region

example:
(Ice Storm of 1998 on HydroQuebec grid)
Simultaneity – Warm & Cold

Between January 5 and 10, 1998, Québec experienced exceptionally harsh weather conditions as three successive storms left up to 110 mm of ice over the south of the province. Though robust and well-maintained, the Hydro-Québec grid suffered unprecedented damage.

Figure 4: Meteorological factors which contributed to the Eastern Canada ice storm of 1998

http://alaingazon.ca/Meteo/verglas.html
Self-Preservation First !!!

a) Thousands of poles, towers and kilometers of lines fell.

b) In area 100 by 250 kilometres, some 116 transmission lines were out of commission, including several major 735 kV power lines and the Quebec–New England HVDC ±450 kV line.

c) At the height of the blackout, some 1.5 million homes and customers, housing three to more than four million people, were in the dark.

d) Blackouts in some areas lasted for 33 days, and 90% of those affected by the blackout had no power for more than seven days.

e) Eventually, the $1 billion level was met – and handily exceeded – and for close to 15 years, the Great Ice Storm of 1998 remained as the costliest insured natural catastrophe in Canadian history.

https://en.wikipedia.org/wiki/Hydro-Quebec’s_electricity_transmission_system
http://www.iclr.org/icestorm98insurance.html

https://merelmarc.wordpress.com/2014/02/12/la-crise-du-verglas-de-1998/
Lessons Learned??

“If the 1998 storm happened now, how would the power system respond?”

1) Restoration times would be much shorter.

Reinforced the grid, such as creating loops, strengthening facilities and pruning trees, reduces the number of customers affected and the extent of damage. **Repair efforts would thus be more localized and take less time.**

2) Certain --- construction standards and methods --- help to make the power system more robust.

Major research and development efforts to better understand events and to strengthen facilities began immediately after the ice storm and continue today.

Test lines have been built at Hydro-Québec’s research institute, IREQ, in order to replicate icing conditions, and to **test and validate specific designs and parameters.**

Causes for Extended Duration Outages

1. Destroyed essential elements (long-time repair)
   A. Energy transport elements (ex. Transformers, T-lines, compensators)
   B. Measurement and control elements (ex. CTs, VTs, VAR control, PMU)

2. Damaged essential elements, which then fail later.

3. Loss of system control communications
   A. SCADA, intranet, satellites (ex. GPS time-stamp)

4. Lack of raw materials/energy/transportation
## Solar Storms – Premonitions?

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Description</th>
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| 1970   | Albertson, Baelen | [Calculated] E-fields have sufficient magnitude to cause disturbances on power systems, and are in agreement with previously recorded values. --- regions with low conductivity are more susceptible to magnetic storm disturbances.  

\[ |E_0| \leq 3.4 \text{ V/km}, \text{ at } 500 \text{ nT, for 1-60min} \] |
| 1972   | Albertson, et al | The importance of localized internal heating in power transformers due to [GIC] is presented.  

\[ \text{GIC of 5 - 100 ampere and more, for minutes} \] |
| 1973   | Albertson, Thorson | K-8 Storm of August 1972: Geomagnetic storms produce quasi-dc currents in 60 Hz electric power systems. These spurious dc currents caused undesirable equipment and system operating effects. |
| 1981   | Albertson, et al | --- load-flow studies made with GIC present in large interconnected power systems in North America |

**THEN:** 1989 Hydroquebec GIC Blackout
Power System GMD Event Response

Lessons: the 1989 Hydro-Quebec GMD event:

‘DC’ Induced Harmonics (via Transformer Magnetic Saturation)

1. Voltage regulating SVCs malfunction -> trip major T Lines
2. Loss of major generation -> frequency collapse
3. Unable to shed load fast enough -> further frequency collapse
4. Self-protection shut down -> lack of adequate after failure strategies
The 2\textsuperscript{nd} Biggest Risk from large GMDs on Grids is the Abnormal Unknown Injected Energy

1. Abnormal Energy enters Grid via highly non-standard paths
   A. ‘DC’ Ground Rise NOT encountered except with GMDs, NO design experience

2. Added abnormal energy causes unknown (unexpected) consequences [harmonics, heating]
   A. How much, how long, where?
The 3\textsuperscript{rd} Biggest Risk from large GMDs is ‘Inadequate Models’

1. Simulation Circuit Models

   A) Coupling from magnetic field to induced earth voltages
   B) Induced earth voltages that cause GICs
      - Source ‘In-Earth’, not ‘on-lines’
   C) GIC effects ‘spread’ into network and load-flow

2. Transformer thermal models with ‘DC’

3. Unexpected System Response

   circuit example:
   
Inadequate Models enhance Risk from large GMD caused Power Apparatus Damage

1. Transformer over-heating with ‘DC’
   A) Heating of Windings
   B) Heating of ancillary parts
   C) Role of harmonics frequency vs stray flux location and magnitude
   D) How to ‘harden’ transformer design from GMDs
   E) Add ‘fast detect and protect’ control of transformers

2. VAR stabilizers

3. Measurement/control devices
GIC Model: Actual Structure

Earth is NOT an Equipotential

Albertson 1981, Wait 1952
GIC Model: Actual Structure

Earth is NOT an Equipotential

Lindahl 2003
GIC Model: Actual Structure

Different Earth Surface Potentials at Every Earth Contact

Albertson 1981
GIC Model: ‘NERC’ Circuit Conflict

Sources not in Earth

Figure 2 — GIC flow through grounded neutral connections of power transformers

[Apparently Used By: World-Power, and PSS®E; Boteler, Overbye, Pirjola and Siemens]
GIC Model: ‘NERC’ Circuit Conflict

The method used is the Induced Voltages in Transmission Lines as voltage sources. This method of calculation is recommended by NERC GMD Task Force.

‘In-Line’ equivalent circuit employed by PSS@E simulator [Siemens2014]
GIC Model: ‘NERC’ Circuit Conflict

Equivalent Circuit for in-line and in-earth voltage source model [boteler]
The 4th biggest risk is from uncertain parameters and values

1. Induced earth surface voltages that cause GICs
   A) Effective earth resistance
   B) Where GICs travel in system

2. Transformer losses with harmonics
Earth Surface Potential Directly changed by earth volume resistivity:

\[ E_y(\omega) = -\frac{Z(\omega)}{\mu} B_x(\omega) \]
Figure 7: Thermal Step Response to a 5 A/phase dc Step [3]
Metallic hot spot heating.
Transformer Heating Models

Figure 12: Capability curve of a transformer based on the thermal response shown in Figures 8 and 9

[nerc TPL-007-1. 2014]
Transformer Heating Models

girgis2013_GIC-hotSpot
Transformer Heating Measurements

Fig. 12. Measured temperature on the tie plate and the tank cover of the 370-MVA transformer under dc excitation.
5th Risk Factor: Unknown ‘expected size’ of GMD event to tolerate

1. Solar event size (magnitude/physical extent)
   - Very large event: < 1 ppm of solar daily energy
   - Statistics consistent for many ‘observables’

2. Many ‘metrics’ for statistics
   - CME mass, energy
   - Earth surface B-fields, DST (equator), local
   - Earth surface E-fields
   - Physical extent of field perturbations
Very Large Solar Events

"It's likely that the Carrington event was also associated with multiple eruptions, and this may turn out to be a key requirement for extreme events," notes Riley. "In fact, it seems that extreme events may require an ideal combination of a number of key features to produce the 'perfect solar storm.'"

In their Dec. 2013 paper, Baker et al. estimated Dst for the July 2012 storm. "If that CME had hit Earth, the resulting geomagnetic storm would have registered a Dst of -1200, comparable to the Carrington Event and twice as bad as the March 1989 Quebec blackout."
The Start of Troubles
Power System GMD Effects

1) Added heating due to eddy current effects in metallic parts within a transformer exposed to high harmonic content magnetic fields.

2) Added heating within transformer windings due to the large added harmonic currents.

3) Added heating within transformer windings due to eddy current losses in the winding conductors and nearby metal volumes.

4) The harmonics produced within a transformer propagate into the power system and cause unplanned response of measurement apparatus.

5) The harmonics produced within a transformer propagate into the power system and cause unexpected reactance and system stability issues.

Heating: highly sensitive to amount and duration of GIC currents, Easily exceeds Standard Levels

Unknown sensitivity To amount and duration Of GIC currents
Power Systems

two key paths for GMD events to disturb an electric power system

(1) is to introduce added abnormal energy via extended power lines

(2) is to disturb communications so the power system is in some sense ‘blinded’ and lacks information needed for normal operation.
Insufficient Clarity of Response-1

- Ambiguous basic electro-magnetic model for coupling GMD energy into the grid,
- Unsubstantiated equivalent circuit models employed by utilities for calculations of the perturbation energy flow into the grid,
- Uncertainty for earth resistivity and how much it changes with weather and climate, especially over the long term,
Insufficient Clarity of Response-2

- Restrictive assumptions about calculated transformer response to coupled GMD energy and lack of experimental test data,
- Unknown criteria, models and testing for the impact of large GMD induced harmonic content,
- Unknown criteria for and coordination of the impact of numerous simultaneous local outages over a broad area including recovery schemes and adequacy of ‘black-start’ contingencies.
Insufficient Clarity of Response-3

• Uncertain models and criteria to evaluate and access the impact of communications loss, especially with the expected greater reliance on centralized automated electronic controls.

• Uncertain preparedness models to deal with large-scale simultaneous outages.
Areas of Uncertainty of Risk

• A validated agreed physical model for GMD energy coupling into the electric grid.
• A validated agreed equivalent circuit to enable accurate calculations of GMD induced energy and currents in the electric power system.
• A better understanding of earth resistivity effects, especially with regard to spatial variations and long-term global weather variations.
• Full or near full-size tests for GMD current effects in loaded transformers, heating and harmonics production.
• Validated modeling for wide area full system tolerance to total system harmonics production.
Solar Storm Questions

(1) Does compliance with FERC directive “779” adequately insure that the defined Baseline event will actually be tolerated by compliant power systems, and

(2) What damage/risk can be expected for GMD events of even greater levels above the defined Baseline event? This Baseline event is considered an ‘extreme’ event by its authors.
What To-Do ‘Next’ to Reduce Risk

1. Develop Quantified ‘Severity’ Scale
   - Reliable early warning forecasting with well quantified scale of severity of approaching GMD events provided near-real-time to utility operators, perhaps a logarithmic scale like earth-quake Richter-Scale.

2. Measure true ‘ground-rise’, Earth-Surface Potentials
   - Over 50 km by 50 km minimum area grid (2 or 3 locations)
   - At least 5 year observations minimum

3. Validate simulation models, design practice
   - Confirm accurate position for GIC circuit sources, impedances
   - Improve, validate transformer heating models
   - Improve, validate transformer design/specification guides for GIC
   - Improve, validate harmonic/stability effects on system due to GIC

4. Model very-wide region system impact
   - Minimum ½ continent-wide simultaneous solar-storm impact
   - Quantify impact of wide-area communications loss
   - Include local system collapse and recovery

5. Evaluate long-term parameter changes
   - Climate-change effects (extreme sensitivity of resistivity)
Earthquake Quantification Example

Incident Categories

Richter Scale

5 6 7 8 9

Cost

$B $M $K $

Disruption

(<10 dead)

Disaster

(10-1,000 dead)

Catastrophe

(>1,000 dead)

Minutes Hours Days Weeks Months Years

Time
Thank You

and thanks to the internet for so many images, etc.